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Corresponding author:
Shakil Ahmad Romshoo;
Email: shakilrom@kashmiruniversity.ac.in

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Glacier thickness and volume estimation in the Upper Indus Basin using modeling and ground penetrating radar measurements

Shakil Ahmad Romshoo[1,2,3], Tariq Abdullah[3,4], Ummer Ameen[1,3] and Mustafa Hameed Bhat[1,3]

[1]Department of Geoinformatics, School of Earth and Environmental Sciences, University of Kashmir, Hazratbal Srinagar, Kashmir, Jammu and Kashmir, 190006, India; [2]Islamic University of Science and Technology, Awantipora Kashmir, Jammu and Kashmir, 192122, India; [3]Centre of Excellence for Glacial Studies in the Western Himalaya, University of Kashmir, Hazratbal Srinagar, Kashmir, Jammu and Kashmir, 190006, India and [4]Department of Planning and Geomatics, Islamic University of Science and Technology, Awantipora Kashmir, Jammu and Kashmir, 192122, India

Abstract

In the Himalaya, ice thickness data are limited, and field measurements are even scarcer. In this study, we employed the GlabTop model to estimate ice reserves in the Jhelum (1.9 ± 0.6 km^3) and Drass (2.9 ± 0.9 km^3) sub-basins of the Upper Indus Basin. Glacier ice thickness in the Jhelum ranged up to 187 ± 56 m with a mean of ~24 ± 7 m, while the Drass showed ice thickness up to 202 ± 60 m, with a mean of ~17 ± 5 m. Model results were validated using Ground Penetrating Radar measurements across four profiles in the ablation zone of the Kolahoi glacier in the Jhelum and nine profiles across the Machoi glacier in the Drass sub-basin. Despite underestimating ice-thickness by ~10%, the GlabTop model effectively captured glacier ice-thickness and spatial patterns in most of the profile locations where GPR measurements were taken. The validation showed high correlation coefficient of 0.98 and 0.87, low relative bias of ~−13% and ~−3% and a high Nash–Sutcliffe coefficient of 0.94 and 0.93 for the Kolahoi and Machoi glaciers, respectively, demonstrating the model's effectiveness. These ice-thickness estimates improve our understanding of glacio-hydrological, and glacial hazard processes over the Upper Indus Basin.

1. Introduction

The Himalaya has the largest glacier area outside the poles (Bolch and others, 2012; Sakai, 2019) sustaining lives and livelihood of millions of people downstream (Immerzeel and others, 2010; Tuladhar and others, 2021). Glaciers in the Himalaya and elsewhere in the world exert a complex influence on land surface and climate processes (Milner and others, 2017; Johnson and Rupper, 2020) and are anticipated to affect the regional hydrological regimes under the projected climate change (Romshoo and others, 2020a; Chen and Yao, 2021). The assessment of land system changes, changes in the local, and regional climate and hydrological regimes and glacial hazards requires an accurate estimate of glacier volume and ice thickness distribution (Huss and Hock, 2018). However, despite far-reaching implications, glacier volume and ice thickness distribution estimates over the Himalayan region are limited largely due to technological limitations, remoteness, and challenging topography (Bolch and others, 2012) and the consequent limited field observations (Wagnon and others, 2013; Zhang and others, 2022). As a result, knowledge about the amount of water stored in these glaciers and their response to changing climate is limited. It is important to note that accelerated glacier melting and the consequent impacts on various dependent sectors have attracted the attention of researchers from all over the world to understand the response and behavior of the Himalayan glaciers (Cogley and others, 2010; Bhambri and others, 2011; Gardelle and others, 2013; Gardner and others, 2013; Kääb and others, 2015; Brun and others, 2017; Salerno and others, 2017; Maurer and others, 2019; Abdullah and others, 2020). However, most of these studies have investigated glacier retreat (Kamp and others, 2011; Pandey and others, 2011), mass balance (Ghosh and Pandey, 2013), glacier elevation changes (Abdullah and others, 2020; Romshoo and others, 2022a), climate change impacts (Rashid and others, 2017) and only a few have studied glacier ice thickness or volume (Linsbauer and others, 2009; McNabb and others, 2012; Frey and others, 2014; Gantayat and others, 2014; Linsbauer and others, 2016; Farinotti and others, 2017; Farinotti and others, 2019; Sattar and others, 2019; Pandit and Ramsankaran, 2020; Millan and others, 2022; Nela and others, 2023). It is pertinent to mention that direct ice thickness measurements over the Himalayan region are available for only about 15 glaciers (Mishra and others, 2022).

The glacier thickness and volume are the basic and most important parameters for projecting the future glacier evolution (Le Meur and others, 2007; Kaser and others, 2010; Gabbi and others, 2012; Immerzeel and Bierkens, 2012; Farinotti and others, 2019; Liang and Tian, 2022), future water availability (Huss and others, 2008), and estimation of future sea-level rise (Gabbi and others, 2012). Information about glacier thickness, besides being required for glacier, volume estimation, is also important for various glacio-hydrological studies (Huss and others, 2008), regional and local climate modeling (Kotlarski and others, 2010) and assessment of